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STAND, a dynamic model for sediment transport and water quality

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Abstract

We introduce a new model–STAND (Sediment-Transport-Associated Nutrient Dynamics)–for simulating stream flow, sediment transport, and the interactions of sediment with other attributes of water quality. In contrast to other models, STAND employs a fully dynamic basis for quantifying sediment transport, thus distinguishing it from the well-known HEC-6 model. This latter, in particular, computes a steady-state form of sediment transport based on an approximation of transient flow regimes by a sequence of steady-state hydraulic conditions. STAND has a three-level structure. The first level accounts for the hydraulics of open-channel flow, using the conventional St Venant equations. The second level computes sediment transport potential and actual transport rates based on the information provided by the first level. In the third level (not discussed herein), changes of nutrient concentrations along the studied river can be computed as a function of nutrient transport, adsorption/desorption of nutrients to suspended sediment, and releases from bed-sediment pore water. Having introduced STAND and compared and contrasted its structure with HEC-6, STAND's performance is evaluated against a comprehensive data set obtained from a section of the Weihe River, a major tributary of the Yellow River, in China, and compared to results from HEC-6. From both visual evaluation and the statistics of the residual time series, it can be concluded that STAND provides the better simulation, notably under conditions of strongly transient stream behavior.
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1. Introduction

Mathematical models have been developed for the purposes of simulating hydraulics, sediment behavior, and water quality components in rivers. Among these models, the traditional civil-engineering-oriented sediment transport models, such as HEC-6, Fluvial-12, and GSTARS 2.0, have the ability to simulate hydraulics, sediment transport, and the resulting morphological changes to the bed. Although satisfactory simulation results have been obtained with these models, their formulations and calibration both leave significant room for improvement.

HEC-6 was initially developed by the U.S. Army Corps of Engineers in 1977 but has been revised many times since, the latest version being Version 4.1, released in 1996 (United States Army Corps of Engineers and Waterways Experiment Station, 1996). It is used to simulate sediment transport, scour, and deposition in open channels with movable beds. Its account of open channel hydraulics is

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simplified, using steps of constant flows that approximate natural hydrographs. Different sediment transport formulae can be chosen to compute sediment transport and morphological changes following hydrologic events can be simulated. The model has been tested and widely used in the past, not only for studies of bed profile changes caused by hydrology and human alteration, but also in studies of the transport and fate of contaminants.

It has been a common practice for models to treat hydraulic behavior as though in a quasi-steady-state, in which a continuous, time-varying quantity describing a hydrologic event is replaced by a series of discontinuous, constant-valued, step functions (United States Army Corps of Engineers and Waterways Experiment Station, 1996; Yang et al., 1998). The consequences of this approximation may not be all that significant when the modeled events are relatively stable, smooth, and slowly changing. However, when the flow simulated is highly transient and unstable, or fluctuating, the quasi-steady-state approach may be a poor approximation. Furthermore, since the hydraulic simulation stage often serves as the basis for simulating sediment or water quality behavior, any deviation resulting from the approximation may be transferred or even magnified in subsequent computations. Sediment transport potential under steady-state hydraulic conditions governs the simulated sediment transport rate in HEC-6 (United States Army Corps of Engineers and Waterways Experiment Station, 1996), while an algebraic equation (as the simplified form of an advection–dispersion equation) is used to describe the dynamic transport of sediment in Fluvial-12 and GSTARS 2.0 (Chang, 1988; Yang et al., 1998). Under highly transient sediment transport conditions, these approaches seem insufficient (Zeng, 2000; Zeng and Beck, 2001).

The general approach to calibrating these models is to gauge how well the model simulates known morphological changes to the river bed, albeit with limited observations. However, the sediment transport processes of these models have not been adequately calibrated with comprehensive and extensive field data, such as time series for discharges and sediment transport rates, which are essential in judging a model's capability to accurately simulate morphological changes to river beds.

With regard to bed degradation, bed surface armoring, and sediment transport, HEC-6 (Version 3.2) has been evaluated with data obtained from a flume study, a man-made canal, and a natural river reach. When used to simulate flume behavior, the model successfully replicated bed degradation, but at the field scale it over-estimated sediment transport at low flows and under-estimated it at high flows. Field measurement of long-term flushing of sand-size particles from the bed material of a natural gravel-bedded river was simulated well. It was concluded that sediment transport had been successfully simulated, except that the model tended to over-estimate low sediment loads and under-estimate high sediment loads (Havis et al., 1996). With regard to prediction of morphological changes, HEC-6 has also been studied with measurements from flumes. Experiments on sediment transport, under two types of hydraulic conditions–steady uniform flow and steady non-uniform flow–have been conducted. Measured bed profile changes were used to test HEC-6, revealing that the model's performance depended on the sediment transport formulae selected, amongst which those of Toffaleti and Yang gave the more satisfactory results. It was also found that the accuracy of the model's prediction was less than satisfactory in regions where there is highly non-uniform flow (Tingsanchali and Supharatid, 1996). Elsewhere, Rathburn and Wohl (2001) combined HEC-6 and GSTARS 2.0 to examine the impact of sediment release from an upstream reservoir on river morphology, especially pools that are critical to fish as winter habitat, but gave no field observations for evaluating their results.

In conjunction with other sub-models, HEC-6 has been used to study sediment transport and related contaminant transport and fate (Rose et al., 1993). Under these circumstances, where simulation results in the long term (40 years) are needed, the use of steady-state hydraulics appears to have been satisfactory. For a study of the Buffalo River, a sediment/contaminant transport model (named DIFHEC) has been superimposed upon HEC-6 (Wen et al., 1994). DIFHEC has the ability to simulate the distribution and fate of contaminants as a result of adsorption onto, and desorption from, surfaces of fine sediment particles, as well as diffusion from pore water in

the bed sediment column. However, here again, very few empirical data were brought to bear on this study.

To summarize, all these varied applications notwithstanding (Prasuhn and Heng, 1990; Jones and Chang, 1991; Rose et al., 1993; Fripp et al., 1994; Wen et al., 1994; Havis et al., 1996; Tingsanchali and Supharatid, 1996), few studies have subjected sediment transport models to a comprehensive data set collected in a natural river with dynamic hydraulics and transient sediment transport conditions. The purpose of this paper is to introduce a new mathematical model (Sediment-Transport-Associated Nutrient Dynamics–STAND) capable of simulating fully dynamic hydraulics, transient sediment transport, and beyond that, water quality issues. Further, the model is then calibrated using a complete, comprehensive, high quality hydrologic data set (from the Weihe River in China). To illuminate the merits of STAND, we also give the result of a comparison between the performance of STAND and HEC-6.

Our motivation for developing STAND is based on the fact that (1) most of the civil-engineering-oriented sediment transport (scour and deposition) models such as HEC-6 and GSTARS 2.0 do not have a water quality component; (2) most water quality models do not have a complete functionality for sediment transport, which plays an important role in determining the transport and fate of various pollutants; (3) models such as HEC-6 and GSTARS 2.0 simplify hydraulics by assuming a quasi-steady-state–replacing a varying hydrograph with step-functions and assuming constant flow during each of the periods; and (4) HEC-6 uses the computed sediment transport potential obtained from various transport formulae as the simulated sediment transport rate, thereby eliminating any transient sediment transport. It is desirable to have a model capable of simulating sediment transport, nutrient transport, and even more importantly, the possible interaction between the two, given the fact the sediment and nutrients are two of the top three sources of pollution impairing a significant portion of waters throughout the United States (USEPA, 1998). It might have been more convenient to add a water quality component to HEC-6, as in Wen et al. (1994). However, given the quasi-steady-state approach to hydraulic behavior and the inability of

HEC-6 to simulate transient sediment transport, that option is not attractive.

2. Field method and source of data

The Weihe River, with a total length of 818 km and a drainage area of 134,767 km^2, is the largest tributary of the Yellow River, which is known for its extremely high sediment concentrations. The long-term average concentration at the Weihe River at Huaxian Gauging Station is 53.4 kg/m^3, and the maximum concentration in 1971 at the lower reaches reached 917 kg/m^3 (Zeng and Pan, 1982). The long-term average concentration in lower reaches of the Yellow River is 37.8 kg/m^3, and the maximum concentration in 1977 at Sanmenxia Gauging Station reached 911 kg/m^3 (Zhou et al., 1983). The upper reaches of the Weihe River are in a mountainous area, while its lower section is in a vast plain, called the '800 li Chin Area' historically known for its abundance of resources and prosperity (a 'li' is a Chinese length unit that is equivalent to 0.5 km; Chin is the name of the first emperor's dynasty). The Weihe valley remains an important area of wealth today and the river has played an important role in maintaining the area's prosperity. On the other hand, the potential problems caused by flooding pose serious threats to people and property in the area. Because of the importance of the area, comprehensive hydrologic data have been collected systematically, persistently, and intensively for the past several decades. Starting from the mouth of the river, where it joins the Yellow River, up to 140 km upstream, more than 40 cross-sections have been allocated for the purpose of measuring channel morphological changes. Nine gauging stations are scattered along the reach, covering a length of 120 km.

The studied reach is a 77.4 km long section of the Weihe River (Fig. 1), with its upper boundary at Lintong Gauging Station, and the lower at Huaxian Gauging Station. The average annual flow at Lintong is 7.075×10^9 m^3/year, and the average annual flow at Huaxian is 7.362×10^9 m^3/year. The average annual sediment load at Lintong is 3.49×10^8 tons/year, and the average annual sediment load at Huaxian is 3.54×10^8 tons/year. The Weinan Gauging Station is located between the upper and lower boundaries of
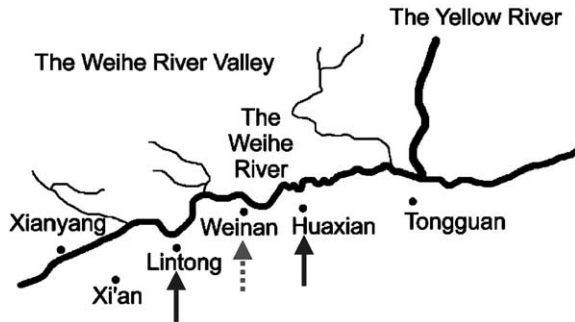
Fig. 1. Weihe River–the Studied reach. Note: all arrows indicate locations of gauging stations where hydrologic data are collected. The solid arrows denote locations where data are used as inputs to the models, and the dashed arrow denotes the location whose data are used for model calibrations.

the reach, with hydrologic data being collected at all three stations on a regular basis. Discharge, surface elevation, suspended sediment concentration, and flow velocity were measured every 4–5 days during regular flow conditions, but measured several times a day under conditions of high flow or high sediment content. Sediment particle size distributions were measured about 10–20 times a year. Channel morphological measurements were conducted several times a year, at least two of which cover all the cross-sections in the studied reach (Yellow River Water Resources Commission, China, 1973).

Data for a 120-day period, taken from the 1973 Chinese Hydrologic Yearbook, were chosen for the computation (by STAND) of hydrodynamics and suspended sediment transport, because of the associated extreme hydrologic conditions. A portion of these data will be used in a similar HEC-6 computation for comparison. For both models, upstream (Lintong Gauging Station) discharge, sediment transport rate, sediment size fraction, and downstream (Huaxian Gauging Station) stage data are used as inputs. The data at Weinan Gauging Station are used as observations to make comparison with the model simulations.

3. STAND: model description

STAND has a 3-level structure: in the first level, one-dimensional open-channel hydraulics are simulated; the second level computes sediment transport under non-equilibrium hydraulic conditions; and nutrient exchange in the water body and suspended and bed sediment is simulated in the third level.

3.1. Hydraulics

STAND's first level uses the St Venant equations for mass conservation and momentum conservation, these being solved numerically using a Preissmann Scheme. The St Venant equations are given by:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial Z}{\partial x} + gAs - q_l U_l = 0 \tag{2}$$

where Q is discharge; A is wetted cross-section area; q_l is rate of lateral inflow; Z is stage level; g is gravitational acceleration; s is the energy slope, which is $n^2 Q^2 R^{-4/3}/A^2$; n is Manning's roughness coefficient; R is the hydraulic radius, which is A/W_p; W_p is the wetted perimeter of a cross-section; U_l is the x component of the lateral inflow velocity; x is the spatial coordinate (longitudinal to the reach); t is the temporal coordinate. The description and numerical solutions to the equations can be found in standard textbooks in hydraulics (French, 1985; Chang, 1988; Chaudhry, 1993).

3.2. Sediment transport

In STAND, suspended sediment has been categorized as suspended sand, silt, and clay. The transport of each class is governed by the advection-dispersion equation,

$$\frac{\partial(AC_s)}{\partial t} + \frac{\partial(QC_s)}{\partial x} - \frac{\partial}{\partial x}\left(AE_s\frac{\partial C_s}{\partial x}\right) - AP_s = 0 \tag{3}$$

where C_s is the suspended sediment concentration of each class; E_s is the dispersion coefficient for suspended sediment of each class; P_s is a production (source and sink) term, which is determined by sediment deposition, entrainment, and transport. For the class of suspended sand, we use a first-order mechanism to describe P_s, i.e.

$$P_s = -k_{sed}(C_s - C_P) \tag{4}$$

where k_{sed} is a coefficient describing the rate at which the actual suspended sediment concentration approaches its potential; C_P is the transport potential for this class of sediment. We hypothesize that k_{sed} has different expressions for deposition and entrainment, which are

$$k_{sed} = k_{sedDep}\left(\frac{l\omega}{q}\right) \qquad (5A)$$

for deposition and

$$k_{sed} = k_{sedEnt}\left(\frac{q}{l\omega}\right) \qquad (5B)$$

for entrainment, where k_{sedDep} is the sediment deposition coefficient; k_{sedEnt} is the sediment entrainment coefficient; q is discharge per unit width; l is characteristic length (we use the distances between consecutive cross-sections here). The sediment transport potential, C_P, is computed using Yang's approach, given by (Yang, 1972; Yang, 1973; Yang and Molinas, 1982)

$$\log C_t = 5.435 - 0.286 \log\frac{\omega d}{\nu} - 0.457 \log\frac{U_*}{\omega}$$
$$+ \left(1.799 - 0.409 \log\frac{\omega d}{\nu} - 0.314 \log\frac{U_*}{\omega}\right)$$
$$\times \log\left(\frac{Vs}{\omega} - \frac{V_{cr}s}{\omega}\right) \qquad (6)$$

where C_t is total sediment transport potential (in parts per million); ω is particle settling velocity; d is particle size; ν is kinematic viscosity; U_* is shear velocity; V is flow velocity; s is energy slope; V_{cr} is critical velocity for incipient motion of particles. Given the fact that suspended sediment transport accounts for over 80–95% of total sediment transport (Yang, 1996), we use the resulting total sediment transport potential, C_t, as the suspended sediment transport potential, C_P.

For the classes of silt and clay, STAND assumes a zero-production term herein, since information regarding silt and clay deposition and entrainment is not available. This means that the model does not consider silt and clay in the process of deposition and entrainment. The same assumption of zero-production is also used in HEC-6.

3.3. Water quality

STAND has a third level for computing changes in sediment-related water quality composition. Its performance in this respect, with regard to a case study of the Oconee River in Georgia, USA, will be the subject of a subsequent paper (see also Zeng, 2000).

3.4. Differences between STAND and HEC-6

The major differences between HEC-6 and STAND are summarized as: (1) HEC-6 uses a quasi-steady-state approximation in simulating hydraulics, while STAND simulates hydrodynamics with full consideration of time derivative terms in the governing Eq. (2) HEC-6 uses computed sediment transport potential as the simulated sediment transport rate, which eliminates any possible transient sediment transport, while STAND seeks the numerical solution of sediment transport directly from the sediment advection-dispersion equation and only uses the sediment transport potential as a targeted equilibrium for the computed quantities to approach. This latter certainly enables STAND to model dynamic sediment transport without simplifications and approximations that may affect the correctness and accuracy of the simulation. It is also different from those approaches used in some other classical civil-engineering models, where simplified solutions and approximations of the advection-dispersion equations (expressed in algebraic-equation form) are used to describe sediment transport behavior (Han, 1980; Zhang et al., 1983; Chang, 1988; Han and He, 1990; Yang et al., 1998).

4. Results and discussion

The parameters of STAND have been adjusted informally in order to obtain reasonable matches with the available observations. Among these, discharge has been replicated reasonably well throughout the entire period of simulation, as shown in Fig. 2. Similar results can also be seen in earlier investigations (Zeng, 2000; Zeng and Beck, 2001), including a further successful evaluation of STAND's hydraulic component using an independent, but similar, data set for the Weihe River in 1974 (Zeng, 2000). Total suspended sediment concentration during a few
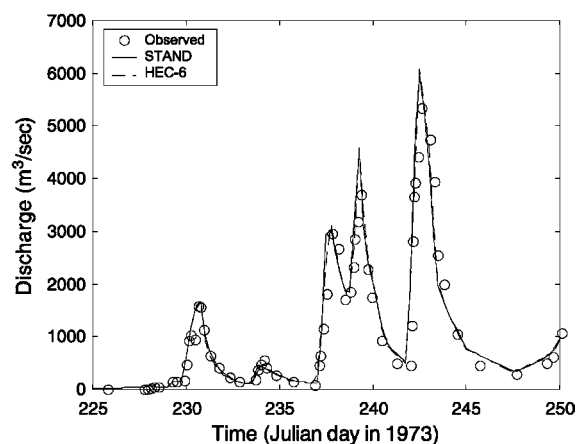
Fig. 2. In-stream flow at Weinan gauging station.

Fig. 3. Suspended sediment concentration at Weinan gauging station.

major hydrologic events are shown in Figs. 3 and 4[1]. Reasonably good replications of the observed events have been obtained from STAND, as evidenced by the statistics (mean, variance, and coefficient of determination) of the residual time series, i.e. the differences between observed and simulated quantities, in Table 1. In short, STAND performs well in simulating suspended sediment transport under transient conditions, which follows mainly from the model's approach to solving the partial differential equations directly, thus providing fully dynamic solutions to hydraulics and sediment transport.

HEC-6, on the other hand, assumes steady-state conditions for both hydraulics and sediment transport, thus omitting the time-derivative terms in the full partial differential equations and simplifying them with algebraic equations that do not fully reflect the true dynamic physical processes. A similar simulation of the suspended sediment behavior using HEC-6 has been conducted for a subsection of the whole period, using a time step of 0.25 days, thus enabling a simulated hydraulic time series closely approximating that observed (Fig. 2). Yang's transport equation has been used (as in STAND) and no silt or clay deposition or entrainment mechanism is defined, so that the transport of silt and clay is also similar to that in STAND. The results of HEC-6 for total suspended
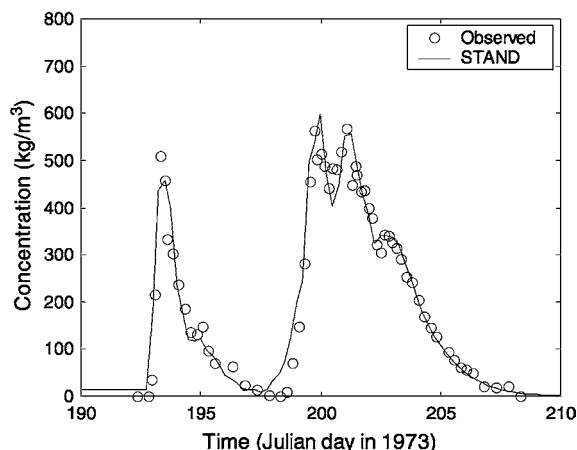
sediment concentration are given in Fig. 4, overlaid with those of STAND and the observed values. It is apparent that some of the earlier events with high-observed sediment concentrations have been under-estimated by HEC-6, while the later lower events have been over-estimated. Statistics of the residual time series of the HEC-6 simulation have also been provided in Table 1. Compared to the statistics of STAND's residuals, those of the HEC-6 residuals have a larger mean, a larger variance, and a much lower coefficient of determination, all of which indicate that STAND's simulation of suspended sediment concentration is a superior replication of the observations.
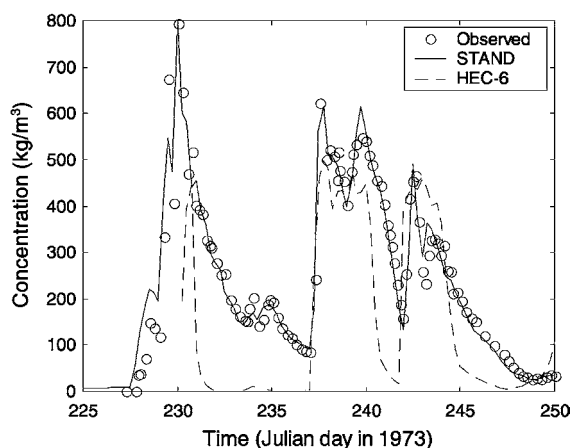

Fig. 4. Suspended sediment concentration at Weinan gauging station.

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[1] Our preferred approach to evaluating the model is by reference to the time-series of discharge and suspended sediment concentration throughout events, as opposed to the status of the bed cross sections before and after the event.

Table 1
Statistics of model performance with respect to suspended sediment concentration (for the hydrologic events from Day 230 to Day 250)

Model	STAND	HEC-6
Mean of residual series (kg/m^3)	3.11	104.0
Variance of residual series	812	18337
Coefficient of determination	0.97	0.31

Note: The coefficient of determination is defined as

$$R_T^2 = 1 - \frac{\sigma_e^2}{\sigma_y^2}$$

where σ_e is the standard deviation of the residual time series (observed value-simulated value); σ_y is the standard deviation of the observed time series.

The most important reason for HEC-6's unsuccessful replication of the observations is its intrinsic assumption of the steady-state for both hydraulics and sediment transport. The equations governing the simplified hydraulics in HEC–6–the continuity equation and the energy equation (United States Army Corps of Engineers and Waterways Experiment Station, 1996)–are greatly reduced versions of Eqs. (1) and (2). When dealing with sediment transport, HEC-6 simply takes the transport potential, computed from the sediment transport formulae, for each time interval of steady-state hydraulics, and assumes no time is required for the sediment concentrations to reach equilibrium. It is apparent that when there is a change in the hydraulics, there will be a change in sediment transport that is gradual; this is neither a sole function of, nor an immediate response to, the changes of hydraulics, as shown in Figs. 2–4. A comparison between Figs. 2 and 4 shows a closely related but non-proportional relationship between discharge and total suspended sediment concentration. It clearly indicates that the HEC-6 computed sediment transport rate, which is in fact the transport potential under steady-state hydraulics, could not represent the actual suspended sediment transport under transient hydraulic conditions.

A very rough representation of particle size distribution–the fraction of silt particles in the total suspended sediment–has been obtained from simulations using both models (Fig. 5). Again, STAND generally captures the major characteristics of the observed phenomenon, although it over-estimates or under-estimates at some points. This same quantity
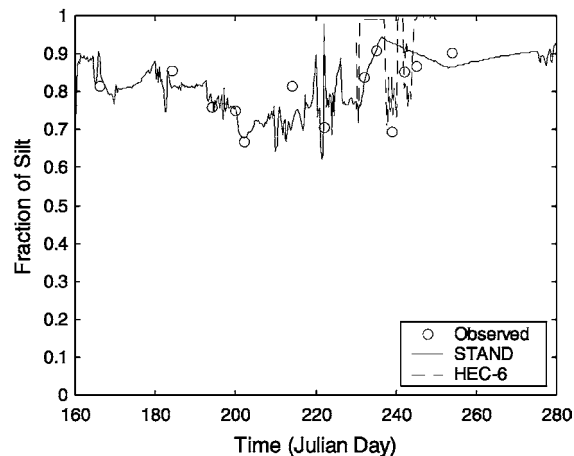

Fig. 5. Fraction of silt in suspended sediment at Weinan.

for HEC-6 is also plotted in Fig. 5, with a more detailed picture being given in Fig. 6. Because of the small number of observations presented, no calibration against this size fraction has been attempted. Fig. 6 only shows the computational results based on calibrations against flow and suspended sediment concentrations. It is understandable that STAND generally provides a better replication of the observed processes, given it performed better in capturing the total suspended sediment concentrations. However, there is a point where HEC-6 appears to have simulated the size fraction better than STAND (around day 239). This is probably caused by the absence of an input data point for the size fraction of sediment in the incoming flow at the upstream
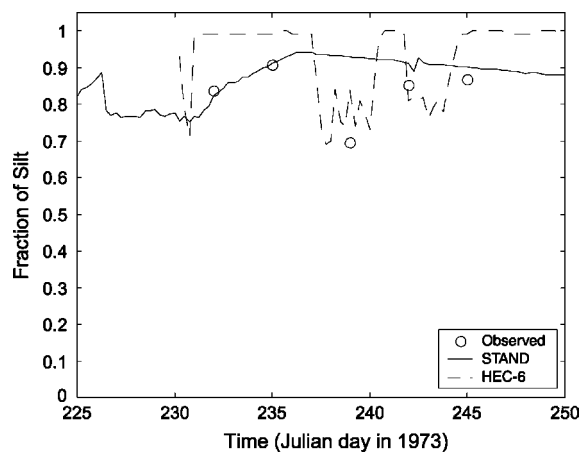

Fig. 6. Fraction of silt in suspended sediment at Weinan.

boundary, the Lintong Gauging Station. Two factors, the accurate and complete information of incoming flow and sediment conditions, and the correct formulation describing the deposition/entrainment processes, affect the quality of STAND's simulation results. Missing an important piece of upstream information probably leads to misrepresentation of the size fraction at the Weinan Gauging Station around day 239. HEC-6, on the other hand, uses the sediment transport potential as the simulated sediment transport rate, so that the apparently reasonable performance at this point is something of a chance coincidence. This is a direct result of, and largely a function of, the magnitude of the hydraulic events (as opposed to particle size fraction).

It can be seen clearly in Fig. 6 that the HEC-6 computation gives fairly high values for the silt fraction (close to, or at, 100%), which means that there is little or no sand transport at all. This is a consequence of the steady-state approach's misrepresentation of a transient phenomenon, where a slowly changing quantity is replaced by abrupt changes, just as upstream conditions (such as incoming flow rate) have been approximated as a sequence of step functions. The dispersion process affects the suspended load during deposition and entrainment, because "certain sediments, especially the fines, require considerable time or distance in settling or in attaining their transport capacity", as stated by Chang (1988). A dynamic approach, as used in STAND, gives a much more realistic representation of the phenomenon and thus more reliable simulation results, because the dispersion process is fully considered and reasonably and correctly formulated.

Finally, several points are worth noting regarding the data set in our study. Suspended sediment concentration reached almost $800 \, \text{kg/m}^3$ at one point and around $500–600 \, \text{kg/m}^3$ at other peak events. This implies that hyper-concentrated flow might have occurred and that non-Newtonian behavior might be of concern. However, past investigations specifically addressed the issue of flow with hyper-concentrations of sediment in the Weihe River and the Yellow River. They indicate that, in these natural river channels, hyper-concentrated flow remains in the turbulent flow regime and no non-Newtonian behavior is encountered

(Zeng and Pan, 1982; Zhou et al., 1983). With regard to particle-size distribution, sand only constitutes a relatively small portion of the suspended sediment (roughly from 10 to 30%). One may therefore question the validity of the suggested functions quantifying the behavior of this size group. However, the very existence of the high sediment concentration events underline the significant magnitude of sand in the suspended sediment during these events, even with the relatively small percentages.

5. Conclusion

When used to simulate long-term sediment transport, scour, and deposition under steady-state hydraulic conditions, HEC-6 provides reasonably satisfactory results, as already shown by previous investigators. However, when highly transient hydraulic and sediment conditions are present, HEC-6 is no longer able to capture the features of these transient events and thus gives simulation results that are less than acceptable. This clearly shows that the simple, convenient steady-state approximation does not work well in a highly dynamic and transient environment.

With the advancement of computer technology, model developers do not have to sacrifice comprehensiveness of a model for faster computational speed or smaller computer memory. STAND, with its capability of simulating dynamic hydraulics, transient sediment transport by size groups, and water quality issues, provides a useful tool in studying problems associated with dynamic hydraulics and transient sediment transport, such as those typical in the analysis of total maximum daily loads (TMDLs). Indeed, STAND has already been used in a case study of sediment-nutrient TMDL analysis for a section of the Chattahoochee River between Lakes Lanier and West Point in Georgia, USA (Osidele et al., 2003). The problem of pollution under transient hydraulic and sediment conditions can thus be addressed with much less concern over the potentially adverse effects of a steady-state approximation.

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